

Twenty Years of Precise Radial Velocities at Keck and Lick Observatories

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Abstract

The precise radial velocity survey at Keck Observatory began over 20 years ago. Its survey of thousands of stars now has the time baseline to be sensitive to planets with decade-long orbits, including Jupiter analogs. I present several newly-finished orbital solutions for long-period giant planets. Although hot Jupiters are generally “lonely” (i.e. they are not part of multiplanet systems), those that are not appear to often have giant companions at 5 AU or beyond. I present two of the highest period-ratios among planets in a two-planet system, and some of the longest orbital periods ever measured for exoplanets. In many cases, combining Keck radial velocities from those from other long-term surveys at Lick Observatory, McDonald Observatory, HARPS, and, of course, OHP spectrographs, produces superior orbital fits, constraining both period and eccentricity better than could be possible with any single set alone. Stellar magnetic activity cycles can masquerade as long-period planets. In most cases this effect is very small, but a loud minority of stars, including, apparently, HD 154345, show very strong RV-activity correlations.

1 The Lick Observatory Planet Search

The precise Doppler planet search at Lick Observatory near San Jose, California, USA ran from 1987–2011. It made use of the Hamilton optical echelle spectrograph in the coudé room of the Shane 120-inch telescope building, built by Steve Vogt (Vogt 1987). On nights that the Shane 120-inch telescope was used with other instruments, the Hamilton spectrograph was often fed via the Coudé Auxiliary Telescope (the “CAT”), a 0.6-meter telescope within the dome that received starlight via a siderostat outside the building, above the coudé room (Figure 1). Together, these two telescopes allowed bright stars to be monitored on virtually any clear night.

The Hamilton Spectrograph was slit-fed, subject to large temperature variations, and not stable at a level that would allow for long-term precise Doppler work without special efforts. Such efforts by Marcy & Butler (1992) came in the form of an iodine absorption cell (Figure 2), following pioneering work by Campbell & Walker (1979) using an HF absorption cell, itself inspired by Roger Griffin’s suggestion that clever exploitation of telluric lines would enable 10 m s⁻¹ Doppler precision (Griffin 1973). The use of iodine as an ideal absorption medium was the suggestion of Robert Howard, of the Carnegie Institute of Washington, inspired by Beckers (1977) (also note the contemporaneous efforts of Libbrecht (1988) and Cochran & Hatzes (1990)).

The Hamilton echelle used a prism cross-disperser, providing broad wavelength coverage, and originally used an 800x800 CCD (later upgraded to 2048x2048). This combination allowed the extremely complex (and unresolved) iodine absorption features to be modeled numerically by computer on a pixel-by-pixel basis, and used to solve for the instrumental profile of the spectrograph (Valenti et al. 1995). Much of this work was done at San Francisco State University by Geoff Marcy and Paul Butler, and their collaborators, including Jeff Valenti at CU Boulder (see Figure 3).

The work at San Francisco State University by Marcy, Butler, and others eventually led to Doppler precisions below 10 m s⁻¹, including r.m.s. velocity variations for some stars as low as 3 m s⁻¹ (Butler et al. 1996). Shortly after the revolutionary announcement of the discovery of 51 Peg b by Mayor & Queloz (1995), Marcy et al. (1997)

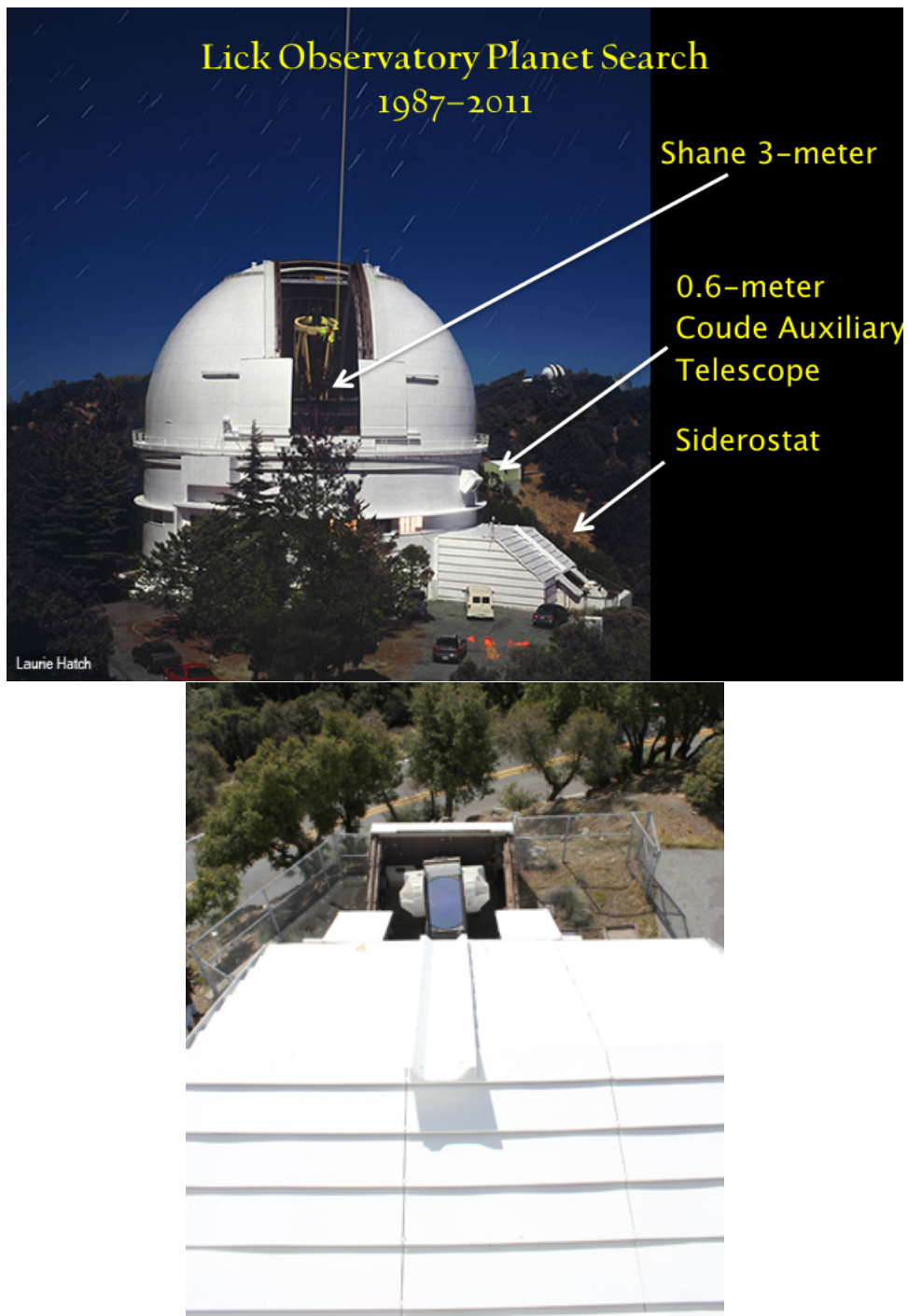


Figure 1: *Top*: The Shane 3-m building. Starlight striking the siderostat traveled up to a port in the side of the building, where it struck a flat mirror before heading to the CAT. The Hamilton Spectrograph is below ground level, beneath the siderostat shed. Photograph by Laurie Hatch. *Bottom*: View of the siderostat from near the port in 3-m building.

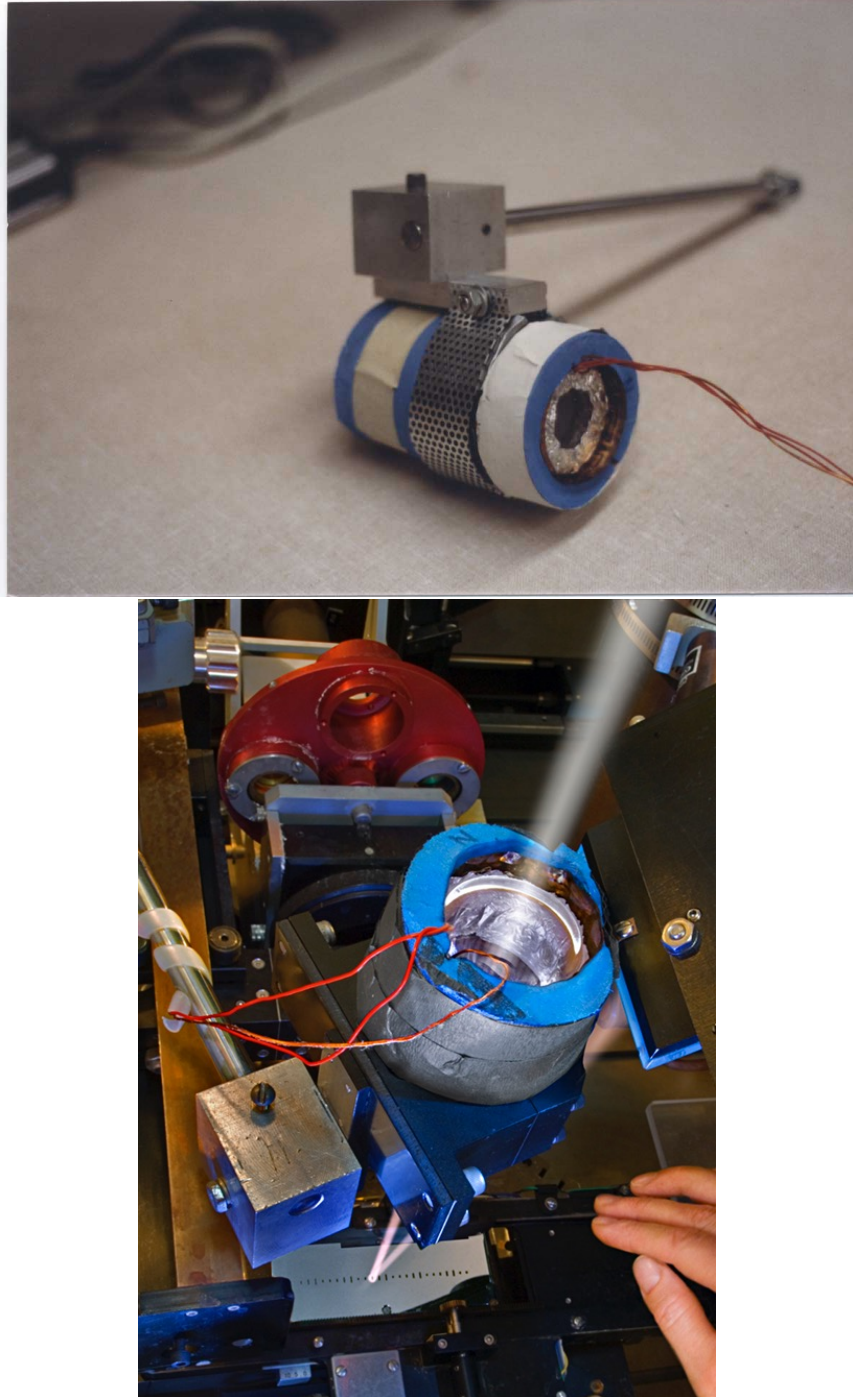


Figure 2: *Top:* The original Lick iodine cell for Lick, designed by Paul Butler and Geoff Marcy. *Bottom:* The Lick cell in position before the slit plate in the slit room of the Hamilton Spectrograph. Photograph by Laurie Hatch.



Figure 3: Early Doppler work at San Francisco State University. *Top*: Paul Butler circa 1988. Butler's work with Geoff Marcy constructing the iodine cell and using its complex absorption features to model the instrumental profile allowed the Lick Planet Search to achieve 3 m s^{-1} r.m.s. variations on some stars (Butler et al. 1996). *Bottom*: The Doppler Lab, with diagnostic plots of the Doppler code lining the wall.

confirmed the discovery, and they parleyed the ensuing attention to their program into access to the computing resources they needed to perform the modeling calculations necessary to thoroughly analyze their data. The Lick Planet Search would go on to announce the next nine exoplanet discoveries, including the first multiplanet system (Butler et al. 1999).

The Lick Planet Search spanned nearly 25 years, and included several upgrades to the spectrograph and detector. In 2011, an error in the temperature controller for the iodine cell caused the insulation to overheat, badly damaging the cell and altering its transmission properties (see Figure 4). This, combined with the superior Doppler precision of other facilities, small aperture of the CAT, and dwindling support for Lick Observatory operations led to the decision to end the Lick Planet Search.

In total, the Lick Planet Search produced precise radial velocity time series from over 14,000 observations of 386 stars. The entire radial velocity archive, and a more detailed description of the project was published by Fischer et al. (2014).

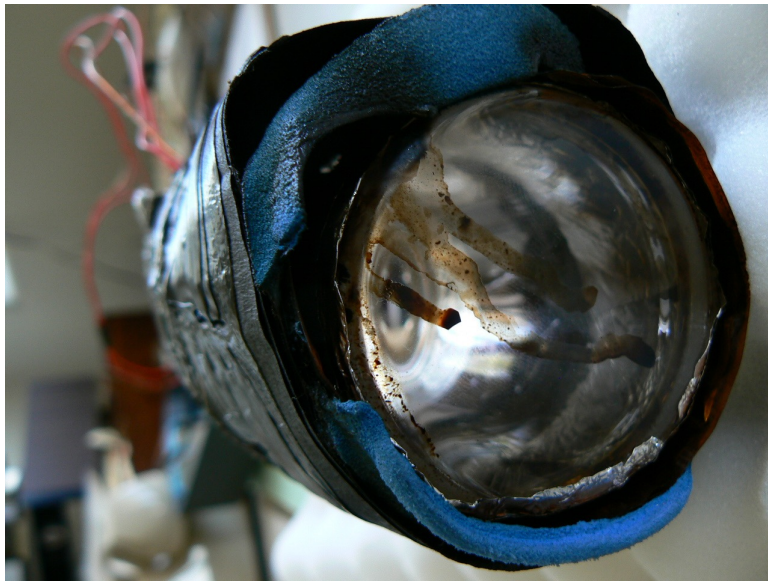


Figure 4: The Lick iodine cell after the temperature controller malfunction that caused it to badly overheat, effectively ending the Lick Planet Search in 2011.

2 The Keck Observatory Planet Search

The construction of HIRES at Keck Observatory by Vogt et al. (1994) allowed the Lick Planet Search to move to Keck Observatory. A new iodine cell was constructed for HIRES (Figure 5), and the Doppler pipeline was applied to this new telescope. Around this time, Geoff Marcy and Paul Butler began to strengthen their ties with collaborators at UC Berkeley, especially Gibor Basri, that had been helping with access to Lick and Keck Observatories and computational facilities. Butler served as a visiting research fellow at Berkeley until 1997 and Marcy as adjunct faculty (Figure 6). In 1999, Marcy moved to Berkeley, joined by postdoctoral fellow Debra Fischer, and in the same year Butler joined the Department of Terrestrial Magnetism at the Carnegie Institute of Washington as a staff scientist.

The iodine planet search at Keck Observatory has been ongoing since 1994. One benefit of the 21+ years of observation at a single site with better than 3 m s^{-1} precision, is the ability to monitor for long-period planets. Except for a detector upgrade in 2004 that improved precision (and created a break in RV continuity, necessitating that a small RV offset be calculated for each star at that date) the data set is uniform and continuous. As such, many long-period planets, including Jupiter analogs, have emerged.

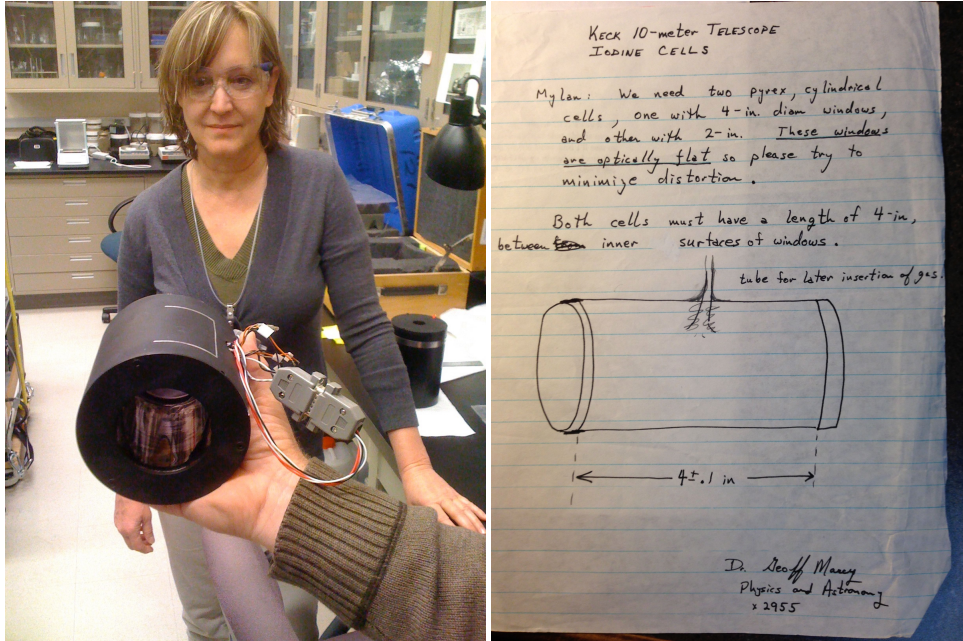


Figure 5: *Left:* Debra Fischer and the HIRES iodine cell during calibration with a Fourier Transform Spectrograph. *Right:* Notes by Geoff Marcy for Mylan Healy, a glassblower at San Francisco State University, for construction of the Keck iodine cell.



Figure 6: Paul Butler and Geoff Marcy at UC Berkeley c. 1994

The first true Jupiter analog announced was HD 154345 *b* Wright et al. (2008), an apparent 1 Jupiter-mass planet in a circular, 10-year orbit around a G star. Wright et al. (2008) noted that both photometry and the activity levels of HD 154345 were consistent with a magnetic activity cycle, similar to the 11-year solar cycle, and were well correlated with the precise radial velocities. Those authors ruled out spurious RV *induced* by this activity cycle by noting that activity cycles are common among the G and K stars in the California Planet Survey sample, and that very few of them show correlated RV variations at the 10 m s^{-1} level, like HD 154345. Indeed, the closest spectral match to HD 154345 in the CPS sample, σ Draconis is the “quietest” star in the CPS sample and the quintessential RV stable star, and it has an even higher activity level and more vigorous magnetic cycle than HD 154345.

However, continued monitoring of HD 154345 since 2008 has shown that the activity cycle continues to be well correlated with the RVs, amplifying the coincidence (see Figure 7). Similar correlations among a small number of other stars of similar spectral type have begun to cast doubt on the planetary hypothesis for HD 154345, and raised a new question about finding Jupiter analogs: why do a small number of stars appear to show strong RV-activity correlations, at the 10 m s^{-1} level and above, while the vast majority show little, if any such correlation?

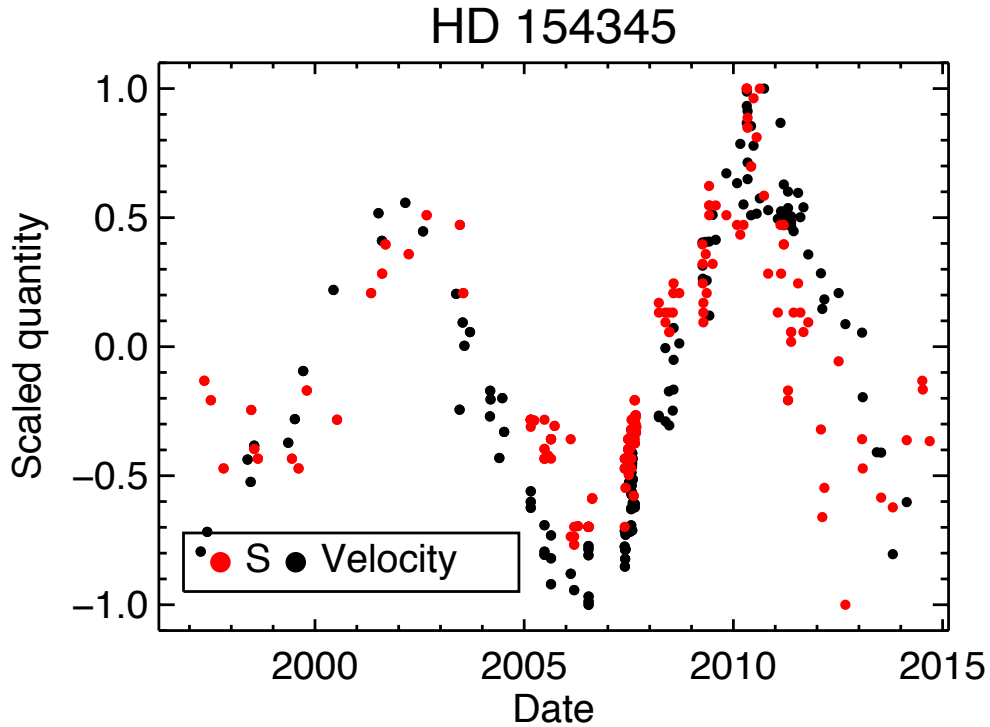


Figure 7: Activity levels measured by the Ca II H & K emission lines and radial velocities, shifted and scaled to emphasize their correlation. There is a discontinuity in both data sets in 2004 because of the detector change. The sinusoidal signal announced by Wright et al. (2008) may not be due to a real planet, but rather a rare, but apparently not unique, activity-induced, spurious radial velocity shift.

Long-period giant planets with higher masses are more unambiguous, because their RV larger amplitudes make them easier to distinguish from the generally noisier activity-induced RV variations, especially when they have Keplerian profiles characteristic of eccentricity. Indeed, despite concerns that activity cycles would make long-period planets hard to detect, contemporaneous observations of activity levels make distinguishing them rather easy (when the periods and phases do not coincide, at least). Figure 8 shows two cases when similar-period activity and RV variations have arisen, but there is little reason to suspect a physical connection.

The contemporaneous planet search efforts with Lick, HET/HRS, ELODIE, SOPHIE, and HIRES provide an opportunity to merge data sets, providing independent measures of the behavior of stars between instrument

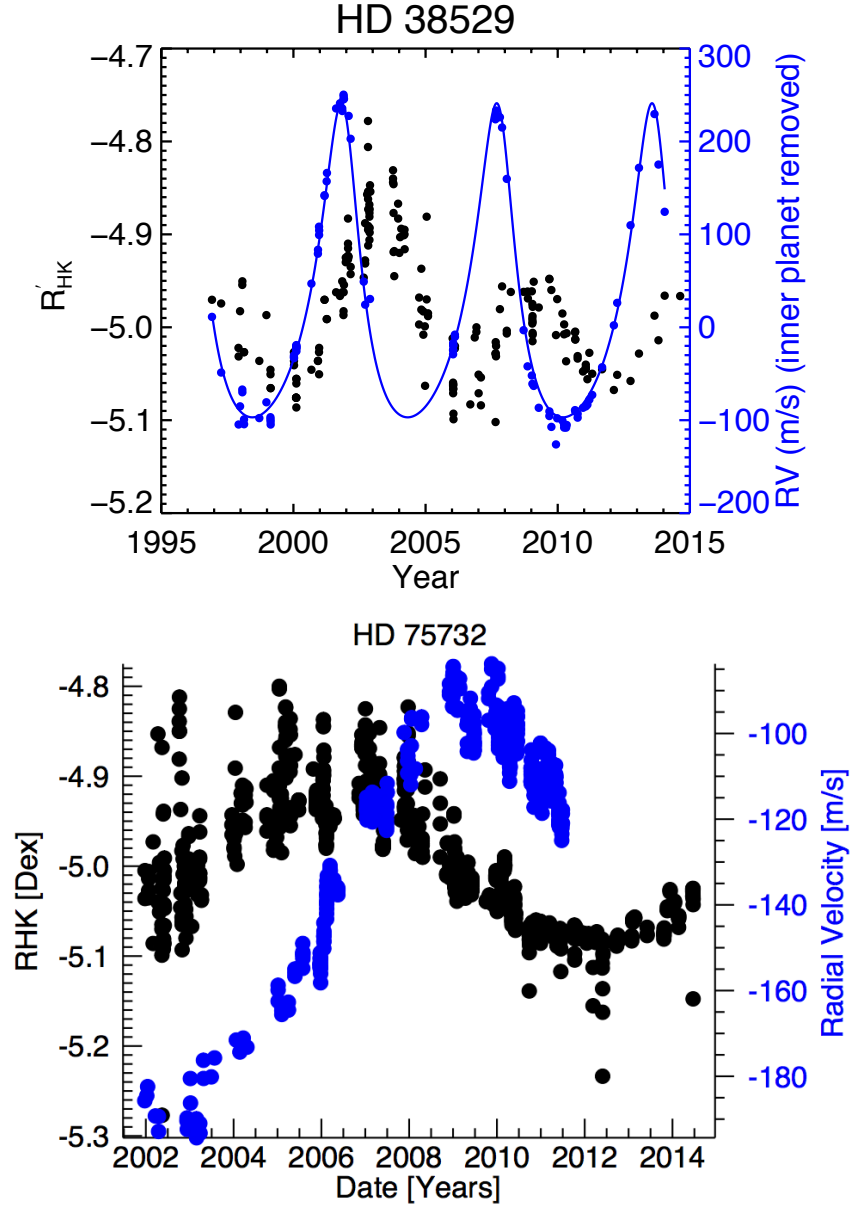


Figure 8: Two examples of activity cycles in stars hosting long-period planets, illustrating how the effects are easily distinguished in most stars. *Top:* The long-period planet HD 38529 *c* (the signal of the short period planet *b* has been removed) shows a similar period to the activity cycle of the star, but shifted in phase, and with a consistent shape, unlike the cycle which has a varying strength. *Bottom:* The outer planet of the 55 Cnc system (inner components removed) similarly induces RV variations with a similar period but different shape and phase from the activity variations. Figures by Jacob Brown.

changes. This is especially important for long-period planets, whose measured eccentricities, amplitudes, and orbital periods may be covariant with an unknown offset introduced by changes to the instruments.

Wang et al. (2012) made good use of both HRS/HET and HIRES observations to find HD 37605 *c*, an outer super-Jupiter with an 8-year, circular orbit. Feng et al. (2015) used published data from Lick, HET, ELODIE, CORALIE, and HARPS, combined with new HIRES data, to calculate good orbital periods for new and updated orbits for several long-period giant planets, including HD 187123 *c* and HD 217107 *c*. These two planets orbit stars already known to host hot Jupiters, and have the largest orbital period ratios with respect to their inner planets (over 1000) of any known system, including the Solar System (see Figure 9).

The emergence of these long-period companions to hot-Jupiter hosting systems reveals that, while hot Jupiters may not be “lonely” in general, when they do have companions, these “friends” are often “cold”, and keep their distance.

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